M A S S A C H U S E T T S  I N S T I T U T E  O F  T E C H N O L O G Y
DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

# 6.101 Introductory Analog Electronics Laboratory

Spring 2015

Laboratory No. 1

**READING ASSIGNMENT:** Review 6.002 notes on resonance, and read the text in this lab.

You should read the documents ***The ABC's of Probes*** and ***The XYZ's of Oscilloscopes***. The links are on the course website under the tab "Reference". Many of you will be using our the ***Tektronix TDS30XXB Oscilloscopes.*** The user manual are also on the course website. Note that the TDS30XXB series are digital scopes with its inherent advantages and disadvantages. For some applications, a better scope for is the ***Agilent MSO-X 3035A***, some of which are in the 6.101 lab. These are state of the art 500Mhz scopes literally straight from the production line!

## OVERVIEW

This is the first of six labs that will occupy you for the first half of the term. This one is probably the longest, but it is also the most "cookbook"-like of all the labs. You will normally receive a new lab on Thursday at 2:30 pm in class; because this lab is longer, and you have an extra couple of days to complete it. Each subsequent lab will deal with topics that will be presented in class and each lab will become more design-oriented and less "cookbooky" as time passes. In other words, we want to take you from training wheels to bicycle racing!

In Experiment 1, we start out to examine the effects of resonance, especially bandwidth, using just a 455 kHz transformer with ***built-in parallel capacitor***, the function generator, and resistors. One resistor will transform our function generator into a current source; the other resistor will be used to control the bandwidth of the parallel tuned circuit.

Then we progress, in Experiment 2, to driving the transformer using a more real world source, a transistor, which has its own unique value of source resistance and is a real current source, rather than a converted voltage source. We are still using a simple load resistor on the transformer secondary in order to control bandwidth; the trick here is that the source resistance of the transistor is a new factor that also affects bandwidth, along with the load resistor on the secondary.

Then in Experiment 3, we replace the load resistor with the diode detector/RF filter/load resistor combination, and we study how the diode changes the effective value of the load resistor and we study how the capacitor can affect the high frequency audio response around 5 kHz, as well as how the bandwidth adjustment can affect the high frequency audio response around 5 kHz, [due to changing the value of the load resistor], which should be the main "adjustor" of the audio bandwidth.

In Experiment 4, we take a look at a simple method of transmitting AM modulation that also gives us a chance to study series resonant circuit behavior. The bandwidth of the series resonant circuit can also have an effect on the high frequency audio response of the complete transmit-receive system.

Then, we go on in Experiment 5 to substitute a receiving antenna for the function generator, which also adds a second tuned circuit, which if it is tuned to the same center frequency as the transformer is tuned, will give us a two-resonant circuit receiver and the combined bandwidth of the two resonant circuits will reduce the audio response around 5kHz even more [the Q of the ferrite rod/coil/trimmer cap arrangement is not as high as the Q of the transformer, therefore the two resonance curves are not the same shape].

The idea is to measure a few high audio frequencies in Experiment 3, say 400, 1000, 3000, 5000 Hz, and then repeat those measurements in Experiment 5 and compare them to see how the addition of the second tuned circuit affects the audio response. [AM broadcasting in the USA is limited to 5 kHz due to our 10 kHz station spacing, in many other parts of the world the high frequency limit is 4.5 kHz and the station spacing on the dial is 9 kHz.]

**OBJECTIVE**

In this laboratory you will transmit an AM radio signal to a rudimentary AM receiver that you will build. This is one of many ways to achieve wireless communication and this experience will help you make a decision on what kind of design project to undertake during the second half of the term. The objective of this laboratory is to gain familiarity with practical series and parallel resonant circuits [tuned circuits], and with RF transmission and demodulation of amplitude-modulated AM signals. You will also learn to use the Tektronix 2445 and TDS 30XXB series oscilloscopes and the Hewlett-Packard 33120B Function Generator/AM-FM Modulator or the Agilent 33220B Function Generator/AM-FM Modulator.

Note that although we have attempted to be relatively thorough in this write-up, there will certainly be things that you may have to figure out for yourself. If you don't know how to do something, you would probably benefit from playing around a bit to see if you can figure it out. There is very little that you can do with the equipment required for this laboratory that can damage it, ***provided you use common sense.*** However, if you are having trouble, don't hesitate to ask for help.

**Please DO NOT USE INDIVIDUAL single-conductor banana plug-to-alligator clip leads to connect from the function generator to your circuits. These wires are unshielded and unpaired and will pick up stray signals and have uncontrolled stray capacitance and inductance.** ***DO USE the BNC [bayonet nut connector]-to-EZ-Hook or BNC-to-alligator shielded cables that are available at the stockroom windows. Insist on them, they were purchased for 6.101 student use.***

***Be sure to retune your IF transformer coil slug every time you make a change to the circuit elements and/or the signal level. The large signal levels we are using tend to saturate the adjustable core in the IF transformer, and this causes the inductance to change. Thus you may have tuned the transformer to resonance at one frequency and voltage level, but at the same frequency with a different voltage level, the circuit may no longer be tuned to resonance. Check it every time!***

***Experiment 1: Q and bandwidth of Parallel tuned circuits.***

***NOTE: THIS LAB REQUIRES A CHECKOFF FOR EXPERIMENT ONE on Tues Feb 10. Get checkoff during staffed lab hours. See course website.***

**A FEW LINES ABOUT LAYOUT:**

Layout on your protoboards is very important, especially at high frequencies. Leads should be kept as short as possible, especially signal leads, to prevent stray inductance and capacitance from affecting your readings.

You must follow these directions for building your circuit, if your circuit does not meet these standards, you will not be checked off until it does.

1. Remove the protoboard assembly from your lab kit. The four protoboards are screwed to an aluminum plate that is attached to the kit by Velcro.

2. **GROUNDING THE SHIELD:** Look at the bottom of the plate. Loosen one of the screws and fasten a small piece of black hookup wire under the screw, and then cut the wire just long enough so that it will reach the top of the protoboard where it can be plugged into your ground bus. Be sure that the anodizing on the aluminum plate is scratched away under the screw so that the wire makes good connection to the plate. There is a special reamer tool located in the lab on a chain near the curve tracer on the metal-topped bench that will quickly and cleanly remove the anodizing from the countersunk edges of the screw hole. Please use it.

   ALWAYS connect this wire to your ground bus. In this way, capacitive coupling will occur between the little metal protoboard receptacles [under each group of five holes] and the metal plate, and the capacitive coupling between adjacent receptacles will be minimized. This metal plate also provides some shielding from the many transmitting antennas on top of the Prudential building, located within eyeshot of your lab space. [See the Joe Sousa RF interference demonstration mounted just to the left of the big bank of lockers in the 34-600 corridor.]

   If coupling between receptacles is still a problem, try spacing out the connections, so that an unused receptacle lies between two used ones. Then, the unused receptacle can be grounded to provide a shielding effect between the two receptacles that are in use.

3. When working on your protoboard, turn the set of boards so that the SHORT side is towards you, and so that the long deep grooves in the four protoboards are parallel to the front edge of the bench.

4. Start wiring using one of the four protoboards. Put the ground bus on the 2$^{nd}$ row from the bottom of the protoboard. Reserve the 1$^{st}$ row for your negative supply bus. Please note that these rows are not continuous…they are disconnected in the center where the center screw comes through. You will need to jumper the left half of the bus to the right half if you need the whole width of the board. Going upwards from the 2$^{nd}$ row, past the vertical columns of five holes each [all connected together], past the groove, the next set of vertical columns, we come to two more rows. You should use the top or 4$^{th}$ row for your positive supply bus, and the 3$^{rd}$ row may be used for another ground bus, or possibly a signal bus in certain cases. HOWEVER, using dual ground busses may

cause ground loops and thus the second ground bus should be used sparingly, and never connected to the first [lower] ground bus except at ONE point.

5. You should strive to copy the schematics we give you as closely as possible in your physical layout on the protoboards. Inputs at the left, grounds at the bottom, positive supply highest, negative supply lowest. We draw the circuits as clearly and logically as possible. Inputs should always be kept away from outputs to avoid undesirable negative or positive feedback. Leads should always be kept as short as possible. Only when you are trying various values of capacitors or resistors, etc. should you use these parts with the long leads that they come with. When you install such parts permanently, be sure to clip the leads short before installing them on the board. Long leads have extra inductance at high frequencies, and long parallel leads have more capacitance between them than do short parallel leads. All these stray or parasitic circuit elements aren't on the schematic, but they have a huge influence on circuit behavior, especially at high frequencies [above 100 kHz].

   IC's and some transistors and JFETs should be mounted so that they straddle the deep groove in the protoboards.

6. When you build larger, more complex circuits, you should start in the upper left corner of the top protoboard, wire from left to right until you run out of space, then continue your circuit from the left side of the next lower protoboard, etc. If you run into problems with circuits on the first protoboard interfering with circuits on the second protoboard, you may need to leave an unused protoboard between the two boards in use.

7. Run your power and ground leads from the lab kit binding posts to your protoboard. Try to keep them as short as possible, and twist all three of them together to form a cable. Use red for positive, black for ground, and pick a nice color for the negative voltage. Bypass the positive and negative leads to ground with 0.1uF 50 volt capacitors at the point where they enter the protoboard.

8. Neatness counts!

Locate the 455kHz Radio-Frequency [RF] transformer in the parts kit, and also a short purple PLASTIC adjustment screwdriver to adjust the coil slug. Build the circuit shown in figure one, ***but please note that you will not need a capacitor, it is built into the transformer and is wired across [in parallel with] the full primary***. You should connect the ground terminal [connected to the "can", which is also a shield from outside interference] to the grounded side of the function generator, and your 'scope ground clip should also be connected to the same ground. You will make a series of 15 measurements using various load and series input resistances and will enter these measurements into Table 1. Then you will make some calculations for the rest of the table, and then we'll ask you to draw conclusions about these circuits by answering some questions.

Keep your hands as far away from the transformer assembly as you can when making adjustments and measurements on this circuit. The stray capacity from your hands will affect your readings. Also, please be aware that the long protoboard tracks along the top and bottom of the protoboards, viewed with the short side of the kit facing you, are ***not*** continuous. They are divided into two sections at the screw in the middle of the long side.

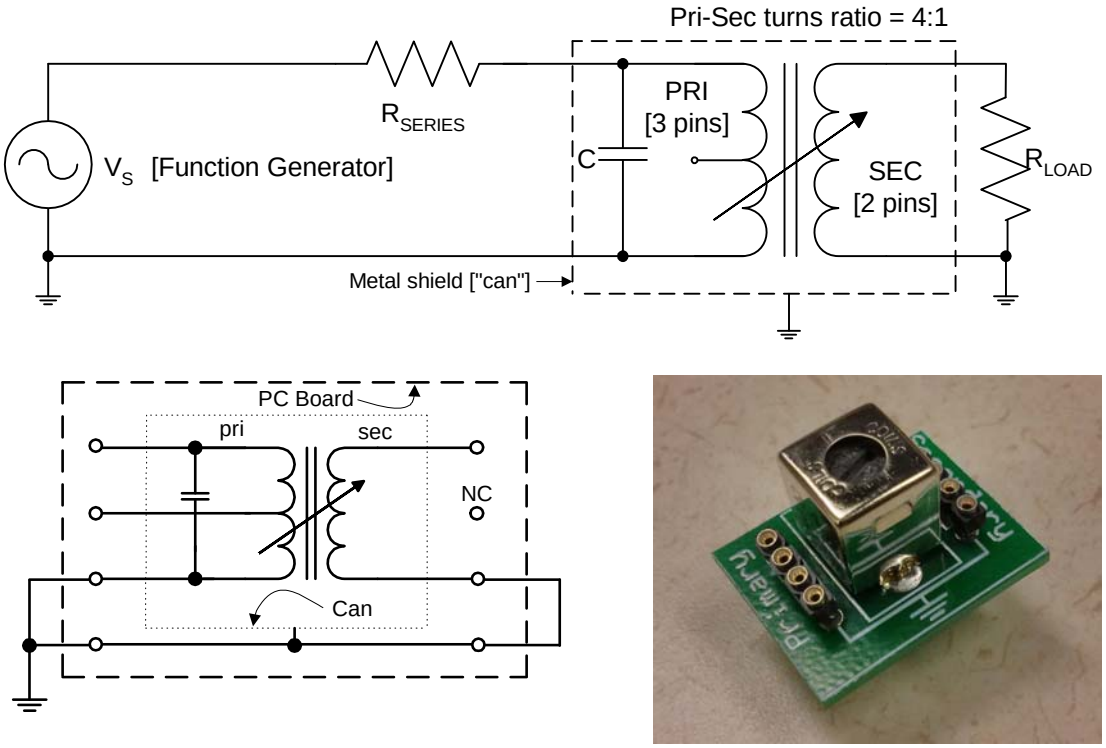



Figure 1: Circuit for parallel resonance, Experiment 1.

1. You should connect your oscilloscope across the output [secondary] of the IF transformer. Connect one side of the secondary to the same part of the circuit that the Function Generator [FG] ground is connected. Connect your 'scope ground clip to the same ground point. Record all results for this experiment in Table 1.

2. Starting with the 10kΩ series resistor in the circuit and no load resistor on the secondary, adjust your function generator to provide about 600 mV peak-to-peak at 455kHz measured across the transformer secondary. While observing the voltage at the output with your oscilloscope, slowly and carefully adjust your transformer coil slug with the plastic screwdriver [NO METAL SCREWDRIVERS] until the output peaks. [DO NOT FORCE THE SLUG. IT WILL HIT BOTTOM, AND THEN FRACTURE INTO PIECES.] You have just adjusted [trimmed] the value of the transformer primary inductance so that it resonates exactly with the built-in capacitor at 455kHz. [**NOTE:** it may be easier to monitor both the input and output voltages paying attention to the phase shift between the two voltages. When they are both exactly in phase, or exactly out of phase by 180 degrees [depends on which secondary terminal is grounded], then resonance is achieved, since the capacitive reactance has cancelled the inductive reactance leaving only resistance.]

3. Set your oscilloscope to measure voltage using the built-in cursors and adjust the function generator output slightly so that the waveform on the 'scope is exactly 600 mV peak to peak. You may be tempted to hook up your Agilent 34401A multimeter to help you make the following measurements, but please consider that the input impedance of the multimeter is 1 MΩ +/– 2% in parallel with 100 pF. This shunt capacitance will be divided by the square of transformer turns ratio and reflected back to the primary, where it will appear in parallel with the capacitor built into the transformer. This will not significantly change the value of the

190 pF primary capacitance since 100 pF /$a^2$=16 is only 6.25 pF. However, the Agilent multimeter's frequency response is NOT specified above 300 kHz, so we have no idea what the numbers on the readout mean at 455kHz! Moral of this story: always consider the effect of connecting test equipment or other external stuff into your circuit.

4. Now slowly change the frequency of the function generator upwards and observe that the amplitude of the waveform on the 'scope is decreasing. Continue to increase the frequency until the peak-to-peak value of the waveform has decreased to 0.707 of the value you recorded in step 3. This is $f_H$ or the high frequency –3dB point. [You can make this job easy by setting your adjustable 'scope cursors to .707 X 600 mV ≈ 425 mV and then just changing the signal generator frequency until the waveform just fits in between the two cursors.]

5. Now slowly change the frequency of the function generator downwards and observe that the amplitude of the waveform on the 'scope is increasing and then decreasing again as it passes through resonance. Continue to decrease the frequency until the peak-to-peak value of the waveform has decreased to 0.707 of the value you recorded in step 3. This is $f_L$ or the low frequency –3dB point.

6. Now repeat the above procedure first with the selection of load resistors indicated in Table 1, and then replace the series resistor with the larger values indicated in Table 1, again with the same selection of load resistors. Notice that as the series resistor is increased and as the load resistor is also increased, the sharpness of the tuning increases and the bandwidth decreases [the –3dB points are much closer to the resonant frequency of 455kHz.] The measure of the sharpness of this resonant peak is called "Q" and its value is infinite for infinite series resistance [***Q1.1 Would infinite series resistance work? Why?*** ]

but in the real world is limited by parasitic resistance and such nasty practicalities as load resistances. [You will have to recheck your output reference levels at 455kHz each time you change the value of either the $R_{SOURCE}$ or the value of $R_L$]. Be sure to set your function generator back to 455kHz each time you set your output reference levels. When you get to the measurements using the 1 MΩ series resistor and the smaller load resistors, you will have to settle for a much lower reference voltage at 455kHz due to the large drop across the 1 MΩ resistor and the loading effect of the load resistors. You should be able to achieve about 80mV peak-to-peak at 455kHz measured across the secondary under the worst-case conditions.

7. When the measurements for Table 1 are completed, use some of the equations below to enter the data in the "calculated data" section of the table. Please remember that the load resistor on the secondary is "reflected" to the primary according to the turns ratio. That is to say, the secondary resistance appears in parallel with the primary but multiplied by the turns ratio squared [$a^2$]. This value is $R_{Lpri}$ in Table 1 on page 8. $R_{eff}$ is the parallel combination of the secondary load reflected to the primary ***in parallel with*** the source resistance. The fact that the calculated and the measured bandwidths are different is explained by the parasitic resistances in the coil and the capacitor, which we are modeling as a resistance in parallel with $R_{eff}$. The primary losses in this circuit are due to the coil wire resistance.

The following equations will be useful in understanding the behavior of parallel resonant circuits and in calculating values for your table. They will be derived in a later section of this lab.

Resonance occurs when $\omega C = \frac{1}{\omega L}$; the magnitudes of the impedances are equal. Due to their equal but opposite locations on the imaginary axis, these impedances cancel each other [for ideal circuit elements only!], **leaving only the resistive elements in the circuit at resonance**.

Solving for the resonant frequency: $\omega_o = \frac{1}{\sqrt{LC}}$ *or* $f_o = \frac{1}{2\pi\sqrt{LC}}$ . Note that the resonant frequency does not depend on the values of any resistances in parallel with both the L and the C; but it will vary with the value of the parasitic [series] resistance of the inductor, caused by the resistance of the fine wire used to make the coil. We shall ignore the existence of this parasitic resistance just now.

Bandwidth is defined as: $BW = \Delta f = f_H - f_L = \frac{1}{2\pi RC}$.

Q of the circuit is defined as $Q = \frac{f_o}{BW}$. With very high resistance [approaching infinity] in parallel with the reactive elements, the bandwidth approaches 0 Hz and the Q approaches infinity.

***Questions:***

Q1.2 Parallel resonant circuits are often presented with the R, the L, and the C all in parallel. However, we are driving our resonant circuit from a voltage source with a low source impedance, and therefore the resistance must be in series with the two reactive elements. Explain what would happen if we placed the resistance in parallel with the reactive elements in this case. What is the value of the source resistance of your function generator?

Q1.3 What is the input impedance that the oscilloscope probe presents to the circuit? [Usually specified as a resistance in parallel with a capacitance.]

Q1.4 How does it compare with the input impedance that the multimeter would present to the circuit?

Q1.5 Will it affect the primary circuit of the transformer in the same way as the multimeter would? Explain.

Q1.6 Review your table of calculated and measured results. What combinations of load and source resistances offer the widest bandwidth? The highest Q? The lowest bandwidth? The lowest Q?

Q1.7 Do all of your measured and calculated values of bandwidth and Q agree? If not, make a list of the differences and explain why they occur. Why does the error get worse as the value of the resistor in series with the function generator gets larger, for the case with infinite load resistance?

Q1.8 Calculate the value of the parasitic resistance associated with the transformer from the data you took using the 1 Megohm source resistance and the infinite $R_L$.

| TABLE 1: RESONANCE DATA USING FG AND SERIES RESISTOR [C = 190 pF]; [a = 4:1] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MEASURED DATA [455 kHz source] | | | | | | CALCULATED DATA | | | | | |
| R-SERIES | R-LOAD | $f_H$ [kHz] | $f_L$ [kHz] | BW [kHz] | $Q=f_o/BW$ | $R_{Lpri}$ | $R_{eff}$ | BW [kHz] | $f_H$ [kHz] | $f_L$ [kHz] | $Q=f_o/BW$ |
| 10,000 Ω | Open circuit | | | | | | | | | | |
| 10,000 Ω | 10,000 Ω | | | | | | | | | | |
| 10,000 Ω | 5,100 Ω | | | | | | | | | | |
| 10,000 Ω | 1,000 Ω | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| 100,000 Ω | Open circuit | | | | | | | | | | |
| 100,000 Ω | 10,000 Ω | | | | | | | | | | |
| 100,000 Ω | 5,100 Ω | | | | | | | | | | |
| 100,000 Ω | 1,000 Ω | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| 1 Meg Ω | Open circuit | | | | | | | | | | |
| 1 Meg Ω | 10,000 Ω | | | | | | | | | | |
| 1 Meg Ω | 5,100 Ω | | | | | | | | | | |
| 1 Meg Ω | 1,000 Ω | | | | | | | | | | |

***Experiment 2: Q and bandwidth of Parallel tuned circuits driven by transistor stage.***

Next, we will repeat some of the previous measurements and calculations using a real-world circuit. The circuit in figure two below is a version of the "long tailed pair" known as the cascode connection. The "long tailed pair" is a fundamental circuit that can also be used as a differential amplifier and which we will study in more detail later in the course. The cascode connection is a common-collector [emitter-follower] amplifier that drives a common-base amplifier. This circuit is very useful, especially at high frequencies, because it prevents the unwanted multiplication of the transistor collector-base capacitance by the stage gain [the dreaded "Miller effect"] when the common-emitter transistor amplifier is used. This effect will be studied later in the term.

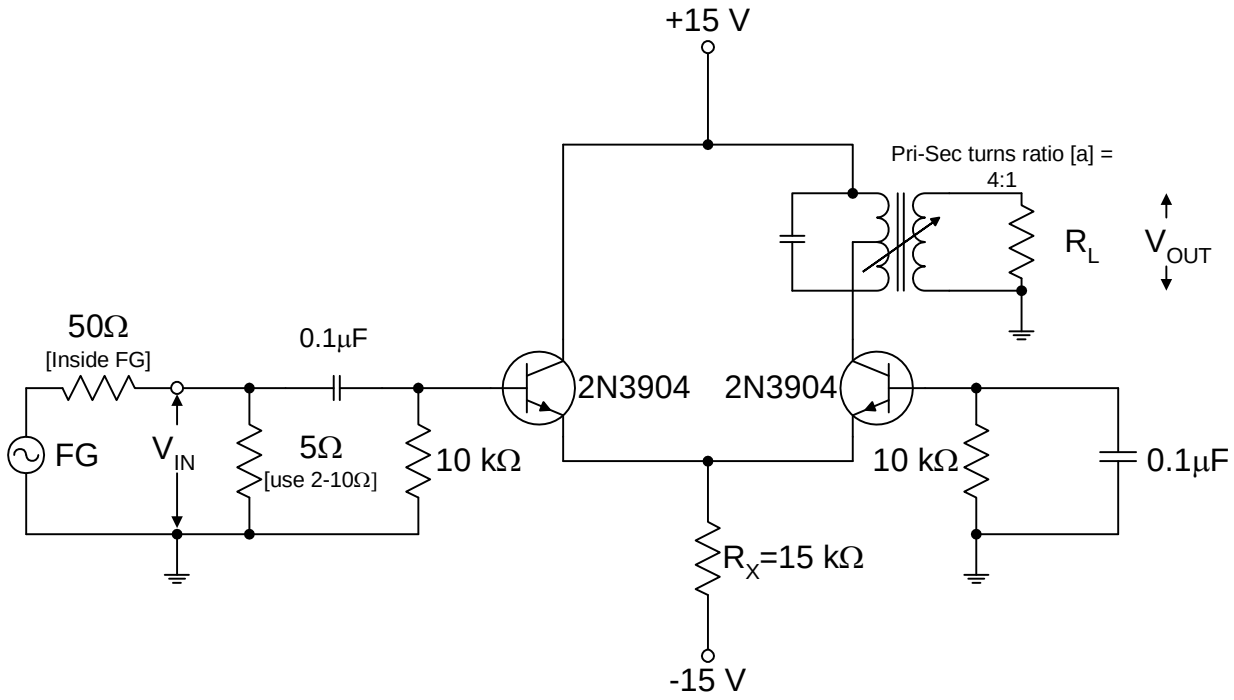



Figure 2: Cascode amplifier circuit driving resonant IF transformer.

In this new circuit, you should understand that the transistor collector terminal is a pretty good current source, with a fairly high source resistance whose value is dependent on the transistor biasing conditions.

Let's simplify figure 2 so that we can derive properly some of the resonance equations that were listed in Expt. 1. We will just concern ourselves with the second transistor and the resonant transformer circuit. The first transistor serves as an emitter-follower and provides a relatively high input impedance and a low output impedance to drive the low emitter input impedance of the common-base transistor that drives the resonant "tank". You can tell that the first transistor is an "emitter-follower" or common-collector configuration because the collector is connected directly to the DC supply [$V_{CC}$] which is an AC ground. You can tell that the second transistor is a common-base configuration because the base is connected to ground through a capacitor. ***Q* 2.1 What is the reactance [impedance] of this capacitor at the 455kHz frequency we are using?**

Figure 3a shows the tuned transformer driven by the transistor current source, and figure 3b shows the same circuit with the secondary resistance multiplied by the primary-secondary turns ratio squared and referred to the primary, and labeled “G” for conductance to facilitate a simpler mathematical analysis.

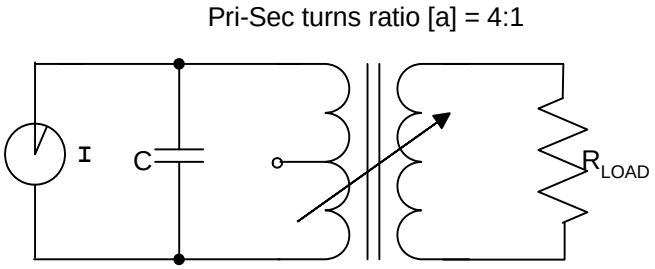



Figure 3a: Tuned Load on IF amplifier

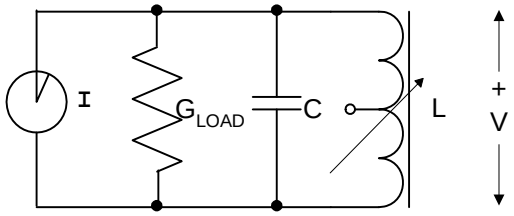



Figure 3b: Secondary Load referred to Primary

Now we will use ***admittance*** notation to solve for the resonance equations. Please remember that we are adjusting the admittance of the inductor using the tuning slug so that it just cancels the admittance of the capacitor ***<u>at 455kHz</u>***, so that the load on the current generator looks like a pure conductance.

From figure 3b:

$$V\left(G + j\omega C + \frac{1}{j\omega L}\right) = -I; \qquad or$$

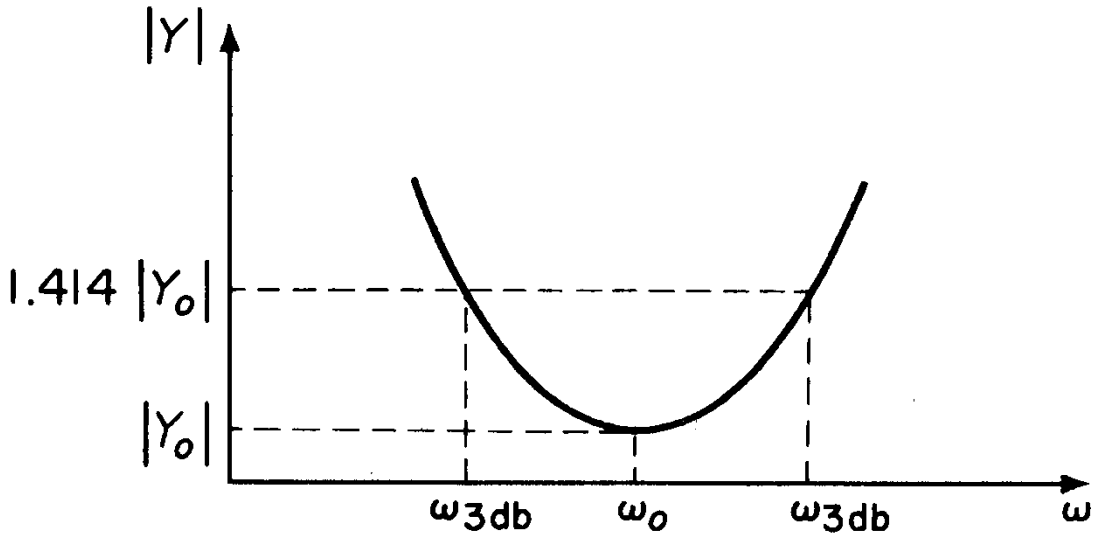
$$V = \frac{-I}{G + j\left(\omega C - \frac{1}{\omega L}\right)} \qquad Eqn.1$$

The circuit is said to be resonant when $\omega C = \frac{1}{\omega L}$, and the resonant frequency is given by

$$\omega_o = \frac{1}{\sqrt{LC}} \qquad or \qquad f_o = \frac{1}{2\pi\sqrt{LC}} \qquad Eqn.2$$

So we see that L and C must have values that will make $f_o$=455kHz and that $f_o$ does not depend on the value of G=1/R. However, at frequencies higher or lower than $f_o$ the values of $1/\omega L$ and $\omega C$ are NOT equal, and the load will have a net inductive or capacitive admittance in parallel that will increase the net value of admittance and thus decrease the output voltage. Just how fast the total load admittance increases from the peak value determines the “sharpness” of the tuning, often called the selectivity of the circuit. This is a desirable quality of these circuits, for selectivity allows us to tune to only the station we want and to exclude adjacent stations that would otherwise cause interference. [Amplitude Modulated (AM) stations in the USA have a maximum bandwidth of +/– 5kHz around the carrier frequency, so in this case we would only be interested in passing frequencies of 450kHz to 460kHz, and excluding the rest. [+/– 4.5 kHz in Europe and elsewhere.]

The bandwidth of a circuit is defined as the difference between the frequencies at which the




response is down 3 dB. [dB=20log$_{10}$V$_2$/V$_1$]. A curve of Y= G + j[ωC-1/ωL] is shown in figure 4.

Figure 4: Plot of Admittance vs. angular frequency, showing bandwidth

The –3 dB points of equation 1 above will occur when real equals imaginary in the denominator:

$$\left|\frac{1}{1+j1}\right| = \frac{1}{1.414} = 0.707$$

Solving for $\omega_{3dB}$: We set the magnitude of the real part of the denominator in Eqn. 1 equal to the magnitude of the imaginary part.

$$G = \pm\left(\omega_{3dB}C - \frac{1}{\omega_{3dB}L}\right)$$

This is rewritten as:

$$\omega_{3dB}^2 \pm \frac{G}{C}\omega_{3dB} - \omega_o^2 = 0$$

Using the quadratic solution:

$$\omega_{3dB} = \pm\frac{G}{2C} \pm \sqrt{\left(\frac{G}{2C}\right)^2 + \omega_o^2} \qquad Eqn.3$$

But, if $\omega_o^2$ is much greater than $(G/2C)^2$, then

$$\omega_{3dB} = \omega_o \pm \frac{G}{2C} = \omega_o \pm \frac{1}{2RC}$$

The bandwidth is the distance between 3dB points, so

$$\Delta\omega = 2\frac{1}{2RC}; \qquad or \qquad \Delta\omega = \frac{1}{RC} \qquad Eqn.4$$

Although the approximation made in equation 3 obscures the fact that $\omega_o$ is not really quite exactly between the two $\omega_{3dB}$ frequencies, the bandwidth is always 1/RC, regardless of the approximation. While the expression $Q = \frac{f_o}{BW}$ is very useful for an intuitive understanding of what "Q" means, there are other ways of expressing Q that we can use to predict the "Q" for the parallel tuned circuit. If we substitute the right side of equation 2 into the numerator, and the rightmost expression for bandwidth from equation 4 into the denominator, we can derive the following useful expression:

$$Q_P = R\sqrt{\frac{C}{L}} \qquad Eqn.5$$

***Thus, we have two major considerations in the design of this frequency-selective resonant circuit given by equations 2 and 4 above. Depending on which circuit elements are easily and practically varied, you can see that resonance and bandwidth may be independently adjusted. Note that L does not appear in the bandwidth equation but that C occurs in both the resonance equation and the bandwidth equation.***

***Directions:***

Build the circuit shown in figure 2. ***STOP: Before connecting the transformer to the +15 volt supply, make sure you have removed the connection from the transformer to ground that you used in Experiment 1. Otherwise, you will apply the full power supply across the primary and melt the fine wires in the transformer and ruin it!*** Please note that you are now going to drive the transformer from the center tap. Connect your function generator as shown at the left of the schematic, so that the output of the generator is connected to the input of the transistor through the coupling [DC blocking] capacitor. [The two 10Ω resistors in parallel in combination with the 50Ω source resistance of the signal generator form a voltage divider to reduce the output voltage enough to prevent overloading this high gain stage.] ***Due to the presence of this voltage divider, you cannot rely on the function generator readout to measure $V_{in}$. Use the oscilloscope to measure $V_{in}$. [The function generator is only accurate for 50Ω loads when set to the "50Ω" setting, and for loads larger than 1kΩ when set to the "High Z" setting.]*** Put your oscilloscope probe across the transformer secondary and adjust your input voltage to produce an output voltage of 2.0 volts peak-to-peak with $R_L = \infty$. Retune the transformer for maximum output when your input frequency is exactly 455kHz. Now take the measurements required to fill in the "Measured Data" section of Table 2. [***You will have to readjust your input voltage at 455kHz each time you change the load resistor in order to maintain the 2.0 $V_{p-p}$ at the output. Also, be sure to retune your transformer with the generator set to 455kHz every time you make a circuit change.*** The cores in these transformers can saturate easily depending on current and voltage levels, and this will change the value of the inductance. Best to recheck that the transformer primary is resonant at 455kHz every time you make a change in the value of $R_L$.]

Then make the calculations required to fill out the "Calculated Data" section of the table. Note that $R_{Lpri}$ is the value of the load resistor reflected to the primary. $A_v = V_{out}/V_{in}$ is the voltage gain. This can be calculated from your measured input and output voltages. $r_o // R_{PARA}$ is the value of the transistor current generator source resistance [$r_o$], in parallel with any parasitic resistance [$R_{PARA}$] that exists in the transformer, and is in parallel with $R_{Lpri}$. [You know the parasitic resistance from Experiment 1.] Together, these three resistances comprise the conductance G that we used above

to derive the resonance equations. To calculate $r_o//R_{PARA}$, use the measured bandwidth that you get from the infinite load resistance case [first line of table 2] and use the bandwidth equation. Copy it into the chart for the other values of load resistance. Then use $r_o//R_{PARA}//R_{Lpri}$ to calculate the bandwidths for the other cases. These calculated bandwidths will probably not be exactly the same as the measured bandwidths in the left hand section of the chart, but they should be close. [Of course the calculated bandwidth for the infinite load resistor case will be the same as the measured bandwidth in order to calculate the value of $r_o//R_{PARA}$.]

Note: Your DMM measures AC voltage in RMS volts; your oscilloscope reads in peak-to-peak volts. In order to get an accurate gain calculation, you will need to convert one kind of voltage unit to match the other. [Your function generator can be set to read either peak-to-peak or RMS volts.]

***Questions:***

Q2.2 What value of load resistance offers the widest bandwidth? The narrowest bandwidth?

Q2.3 What is the value of load resistance that comes closest to giving the bandwidth discussed above as appropriate for AM reception in the USA?

Q2.4 What are the high and low –3dB frequencies you obtained with this value of $R_L$?

Q2.5 What would happen if we decided to vary C instead of L in order to tune this parallel tuned circuit to 455kHz?

Q2.6 Why do you think that the gain decreases as the value of load resistance decreases?

| TABLE 2: RESONANCE DATA USING CASCODE AMPLIFIER AND CENTER TAP [C = 190 pF]; [a = 4:1] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MEASURED DATA [455 kHz source] | | | | | | | CALCULATED DATA | | | | | | | |
| $V_{in\ P\text{-}P}$ | $V_{out\ P\text{-}P}$ | $R_L$ | $f_H$ [kHz] | $f_L$ [kHz] | BW [kHz] | $Q=f_o/BW$ | $r_o//R_{PARA}$ | $R_{Lpri}$ | $r_o//R_{PARA}//R_{Lpri}$ | BW [kHz] | $f_H$ [kHz] | $f_L$ [kHz] | $Q=f_o/BW$ | Av |
| | 2.0 V p-p | Open ckt. | | | | | | | | | | | | |
| | 2.0 V p-p | 10,000Ω | | | | | | | | | | | | |
| | 2.0 V p-p | 5,100 Ω | | | | | | | | | | | | |
| | 2.0 V p-p | 1,000Ω | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |

***Experiment 3: Detector for Amplitude Modulated Signals***

**[Note: This detector will be connected to the IF transformer secondary in place of the load resistor that was used in the previous experiment.]**

Now we have a useful circuit that will both amplify and select a narrow band of desired frequencies. Next we need to prepare a circuit that will demodulate or detect an AM signal.

The expression for an amplitude-modulated signal is:

$$v = A_c \cos\omega_c t + \frac{KA_m}{2}\left[\cos(\omega_c - \omega_m)t + \cos(\omega_c + \omega_m)t\right]$$

where "c" subscripts refer to the carrier frequency [in this case it's 455kHz] and "m" subscripts refer to the modulating frequency which is an audio frequency between 50Hz and 5kHz. K is a scaling factor. By inspecting this equation, we can see that an AM modulated signal contains three frequencies: the carrier frequency and both the sum and the difference of the carrier frequency and the audio signal. When the audio is turned off, the carrier is the only signal. Figure 5a shows a sketch of an AM modulated signal, with the carrier frequency exaggerated [normally the carrier frequency would be so much larger than the audio frequency that the individual carrier waveforms would blend together]. Figure 5b shows the frequency spectrum of the amplitude-modulated signal.

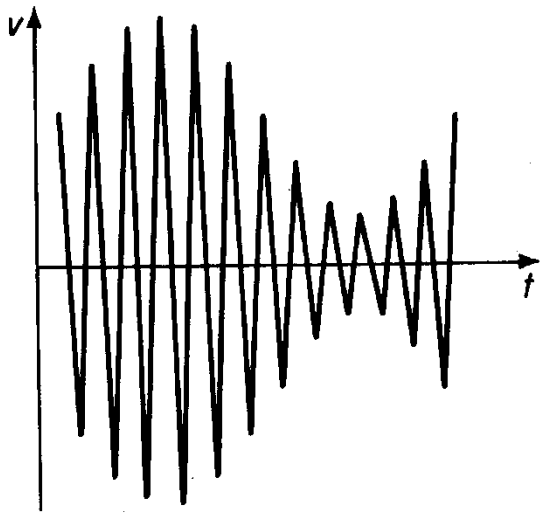



Figure 5a: Amplitude-modulated carrier

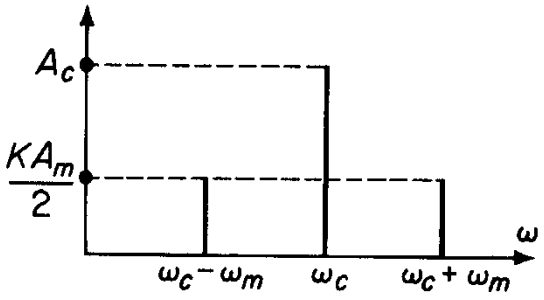



Figure 5b: Frequencies in modulated carrier wave [not to scale]

In order to demodulate and recapture the audio we need to remove the carrier. If we examine figure 6a we can see more clearly how the peaks of the carrier wave approximate the much lower audio frequency [again, the spacing here is exaggerated for clarity]. Note how there appears to be two complete audio waveforms in figure 6a; we can dispense with one of them, and that is exactly what the diode in the detector circuit of figure 6b does. And the remainder of the circuit is simplicity itself: a low pass filter! Of course it's intuitive that to remove the carrier we need to filter out the high frequencies and save the low audio frequencies.

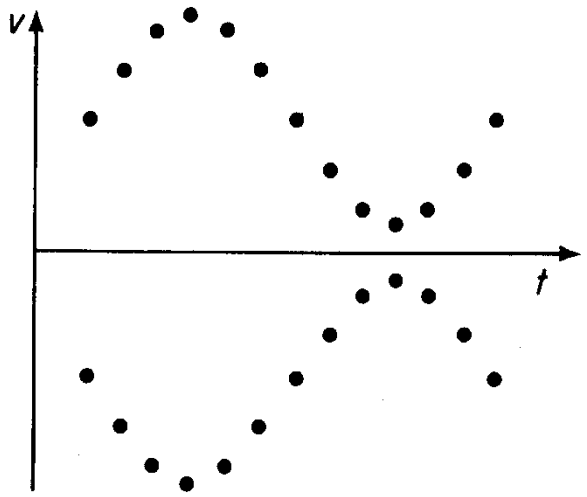



Figure 6a: The carrier peaks outline the audio frequency

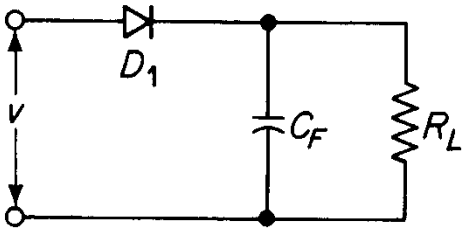



Figure 6b: AM detector circuit
Use a 1N914 or 1N4148 for $D_1$

Until now, we have been substituting a simple load resistor, $R_L$, for the detector circuit, and you should have learned that the value of $R_L$ is reflected to the primary of the transformer and is the primary element in determining the circuit Q and therefore the bandwidth. Bandwidth control is very important in AM to reject unwanted modulation from adjacent stations. Now we must determine a method of finding the input resistance to the detector so that we can control the bandwidth of the modulated signal.

When an AC signal is rectified and then used to charge a capacitor, we have produced a fairly constant DC voltage across the storage device [the capacitor]. There will be some slight ripple on top of this DC voltage, due to the tendency of the capacitor to discharge into the resistor, but let's ignore that ripple just now. Our task is to determine an input resistance looking into the detector just before the diode; let's call it $R_{eq}$ [for equivalent]. We'll calculate this resistance by assuming that the DC power dissipated in the load $R_L$ is equal to the AC power delivered by the transformer carrier signal into $R_{eq}$.

Assuming that $C_F$ charges up to the peak value of the carrier voltage, then

$$P_{DC} = \frac{V_p{}^2}{R_L};$$

The ac power dissipated by the transformer source in the equivalent resistance of the detector is

$$P_{AC} = \frac{\left(\frac{V_p}{\sqrt{2}}\right)^2}{R_{eq}} = \frac{V_p^2}{2R_{eq}}$$

If we equate the input power with the output power, then it is easy to see that $R_{eq} = R_L/2$. Therefore, we need to choose $R_L$ first, as it controls the bandwidth of the tuned circuit. Choose a value for $R_L$ that will give a bandwidth of 10kHz [+/– 5kHz] around the 455kHz carrier frequency, as measured across the IF transformer primary. Next, we could choose $C_F$ from what we know about low-pass filters. However, in this case we are not sure what kind of source resistance the

transformer secondary and the diode provide. If we could easily estimate or measure these values, then we could quickly design the low pass filter. Instead, we will design the filter empirically by first trying a value for $C_F$ equal to 0.01 μF and then modulating the carrier with 400 Hz at 50% modulation. To do this, keep your function generator carrier frequency at 455kHz and then turn on the AM modulation function and adjust for a 400 Hz modulating frequency at 50% modulation [consult the function generator manual, a copy is available from your instructor].

Put your 'scope across the detector load resistor and observe the detected signal. Record the output voltage and then increase the modulating frequency to 1kHz, 3 kHz, and 5kHz. Record the level of audio output voltage for all four of these test frequencies. If the output voltage at 5 kHz is not 3 dB down from the voltage recorded at 400 Hz, then you will need to increase $C_F$ until the 5kHz signal is 3dB down. [If you have a great deal of trouble getting the response at 5kHz to hold up, you may need to choose a different $R_L$ in order to get a wider bandwidth from the transformer, especially if you find yourself using smaller and smaller capacitors and you are starting to see a lot of carrier ripple in your audio output.] Record the values of these two circuit elements. [If the output is more than 3dB down at 5kHz, then you will have to start over with a smaller value of $C_F$ and then add capacitance as necessary.]

***NOTE*: At this point, you may not be able to see the modulating [audio] frequency at the output of the detector. You may just see a distorted ghost of a waveform.** This is due to a very important characteristic of high "Q" [lightly or under-damped] resonant circuits, namely: when you stimulate a high Q resonant circuit with a pulse, a square wave, a part of a sine wave, most *anything*, the resonant circuit will return a sine wave, which is its natural response. Therefore, in previous sections of this lab, you could have been overdriving the transistor stages with a large enough sine wave input signal to produce "clipping" [a square wave] in the transistor driving the tank. However, since the output load is a high Q resonant circuit, the response to a square wave input will be a sine wave. Almost like magic! Now this is fine as long as we are talking about unmodulated signals, but when we take an amplitude-modulated sine wave, send it at too-high a level into a transistor amplifier and clip the signal, well, we have just removed the modulation, the very thing we are trying to detect! Therefore, if you do not see any audio sine waves at the output of your detector, first make sure you are modulating your carrier, and then turn down the carrier amplitude [signal generator output] until you see the proper audio output from the demodulator**.**

***[A good way to observe this, highly recommended, is to put your scope probe between the emitters of the transistors and ground. (The emitter of the left-hand transistor is the output of that transistor, and the emitter of the right-hand transistor is the input of that transistor.) It's a little easier to observe this on the scope, with the modulation turned off. Now, crank up your input until you see evidence of "clipping", one half of the sine wave is missing. Then, move your scope probe to the collector of the right-hand transistor and observe that the full sine wave appears there! The tank is responding to the stimulus of a half-sine by returning its natural response…a sine wave!]***

When you are making your measurements at 400 Hz, please also measure the DC voltage present at the detector output. Increase the modulation level to 80% and record the DC voltage again. Reduce the level of RF input to the circuit and record any change in DC voltage.

***Questions:***

Q3.1 If the RF signal level at the input to the diode detector is less than 500 mV, what will the output of the detector be?

## ***Experiment 4: Transmitting AM signals; Series Resonant Circuits***

NOTE: PLEASE BRING A PORTABLE AM RADIO TO LAB FOR THIS EXPERIMENT. A FEW AM RADIOS WILL BE AVAILABLE AT THE STOCKROOM WINDOW.

You have built and analyzed much of the circuitry required to amplify, bandwidth-limit, and detect AM radio signals. Now it's time to transmit some amplitude-modulated RF [radio-frequency] signals. We will continue to use 455kHz in most of our work since we have designed our receiving circuits to be sensitive to this frequency. This frequency is the same as the 455kHz used in all modern AM radios internally as the Intermediate Frequency [IF]. Most current AM radio design uses the superheterodyne method of receiving, where all the signals in the AM band [530kHz to 1.7MHz] are converted in the receiver to the IF frequency. This allows us to customize most of the amplifying stages in the receiver to perform well at only this frequency, as you have just done in Experiment 2. Normally one would not choose to broadcast using 455kHz, as it could not be received on normal AM radios and is the same as the standard IF frequency and so would cause interference. However, our transmissions will be limited to 10 feet or so and also will be contained within this building due to the shielding built into the building for frequencies in the AM band.

Antennas for transmission or reception fall into two broad categories: **1.** physically resonant [the antenna is ¼, ½, ¾ etc. of a wavelength, depending on whether the antenna is end-fed or center fed] and **2.** physically small compared to one wavelength, i. e., less than 0.1$\lambda$. Resonant antennae are useful at higher frequencies where the wavelengths are shorter than they are in the AM band. An antenna resonant at 455kHz would have to be almost 200 feet long! Therefore we are using a physically small antenna. A physically resonant antenna looks very close to a pure resistance when it is driven as a transmitting antenna; however a small antenna may look inductive or capacitive depending on the frequency. Our antenna looks inductive at 455kHz, therefore in order to drive a useful amount of current into the antenna, we will have to series resonate the antenna with a series capacitor in order to cancel out the impedance due to the inductance.

### ***Series Resonance Analysis:***

Series resonant circuit analysis is identical to that of parallel resonant circuit analysis, except that we shall use impedance concepts rather than admittance notation. The bandwidth curve/admittance plot of figure 4 can be converted into the impedance curve for the series resonant circuit by replacing the Y's with Z's! For a simple series R-L-C circuit driven by a perfectly resistanceless voltage source:

$$V = I\left(R + j\omega L + \frac{1}{j\omega C}\right); \qquad or$$

$$I = \frac{V}{R + j\left(\omega L - \frac{1}{\omega C}\right)} \qquad Eqn.5$$

The circuit is said to be resonant when $\omega L = \frac{1}{\omega C}$ and the resonant frequency is given by

$$\omega_o = \frac{1}{\sqrt{LC}} \qquad or \qquad f_o = \frac{1}{2\pi\sqrt{LC}} \qquad Eqn.6$$

The –3 dB points of equation 5 above will occur when real equals imaginary in the denominator:

$$\left|\frac{1}{1+j1}\right| = \frac{1}{1.414} = 0.707$$

Solving for $\omega_{3dB}$ by setting the real part of the denominator equal to the imaginary part in Eqn. 5:

$$R = \pm\left(\omega_{3dB}L - \frac{1}{\omega_{3dB}C}\right)$$

This is rewritten as:

$$\omega_{3dB}^2 \pm \frac{R}{L}\omega_{3dB} - \omega_o^2 = 0$$

Using the quadratic solution:

$$\omega_{3dB} = \pm\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 + \omega_o^2} \qquad Eqn.7$$

But, if $\omega_o^2$ is much greater than $(R/2L)^2$, then

$$\omega_{3dB} = \omega_o \pm \frac{R}{2L}$$

The bandwidth is the distance between 3dB points, so

$$\Delta\omega = 2\frac{R}{2L}; \qquad or \qquad \Delta\omega = \frac{R}{L} \qquad Eqn.8$$

Although the approximation made in equation 7 obscures the fact that $\omega_o$ is not really quite exactly between the two $\omega_{3dB}$ frequencies, the bandwidth is always R/L, regardless of the approximation. Since Q is still defined as $Q = \frac{f_o}{BW}$, in this case $Q = \frac{2\pi f_o}{\frac{R}{L}} = 2\pi f_o \frac{L}{R}$. ***Therefore, to achieve a high "Q" in a series resonant circuit we will have to use a large inductor [and therefore a small capacitor]. Contrast this with the case of parallel resonance, where we showed that to achieve a high "Q" and thus a very narrow bandwidth we would have to use a large capacitor [and therefore a small inductor].***

Fortunately, our Agilent Function Generators provide both AM and FM modulation and plenty of RF output to drive our antenna. If more than one of you is operating at the same time in the lab at the same frequency, you may find that you are interfering with one another. Therefore, you may wish to turn down the output of your function generator to a level that will allow you to receive your own signal, but which will prevent your signal from reaching another's receiver. It will also be best if those transmitting at the same time locate themselves to distant corners of the lab!

Obtain a 6.101 loop antenna. This is a one-foot square wooden form with ten turns of wire wound on it in a single layer flat coil. You will also need a "trimmer" capacitor, which is an adjustable capacitor with three legs on it. **These legs will NOT fit into the protoboards, so don't even think of trying it.** Two of the legs of the capacitor are electrically connected together and to one

plate; the third leg is the other plate. Please solder short pieces of hook-up wire onto two legs, and then insert the trimmer into the protoboard. DO NOT USE YOUR KIT PROTOBOARD, USE A FREESTANDING PROTOBOARD ON THE LAB BENCH OR GET ONE OUT FROM THE STOCKROOM.

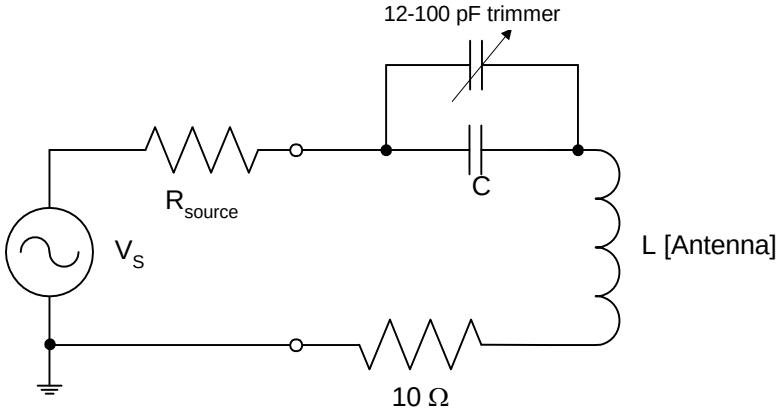



Figure 7: Antenna tuning circuit for transmitting AM carrier from function generator.

Connect the circuit shown above in figure 7. Make sure that the modulation on your function generator is turned off. Be sure to use shielded cable [BNC to E-Z hook or BNC to alligator clips] between the function generator and the protoboard. Look on the frame of the loop to find where the inductance of the loop is marked and calculate the required capacitance needed to achieve resonance at ***540kHz, NOT 455kHz:*** $f_o = \frac{1}{2\pi\sqrt{LC}}$. Make up this capacitance by selecting fixed capacitors from your kit or from those available from the stockroom window and placing them in parallel with the trimmer cap. Adjust the function generator to full output, 20 volts peak-to-peak at ***540 kHz***, not 455kHz. [***Q4.1 Why does the function generator amplitude display show a voltage value that is incorrect?]***

Connect one channel of your 'scope across the 10 Ω series current-measuring resistor, making sure that the ground clip is connected to the side of the resistor that is connected to the signal generator ground. **[The 'scope ground clip is permanently connected to electrical ground.]** Adjust the 'scope amplitude control for the channel across the resistor as required to see a signal [the signal level will be very low until resonance is achieved].

We are trying to obtain maximum current into this series resonant circuit, so your main task will be to monitor the voltage across the 10 Ω resistor as you tune the circuit. You may have to add or subtract some of the fixed capacitors that you have installed, but when the combined value of the fixed capacitors plus the trimmer is correct, you will be able to tune the trimmer and observe the voltage across the 10 Ω resistor pass through a maximum. [***Once again, it may be easier to monitor the output voltage of the function generator on one 'scope channel, and the voltage across the resistor on a second channel, and make your adjustment until the phase angle between the two waveforms is either 0 or 180 degrees, depending.]*** When the trimmer is tuned to produce this maximum, you have achieved series resonance and are driving maximum current

into the antenna. Once resonance is achieved, you may remove or short out the 10 Ω resistor, which will increase the current into the antenna somewhat, and lower the bandwidth as well.

Now, adjust your function generator so that your carrier is AM modulated with a 400Hz modulating frequency at 100% modulation. Turn on your AM radio and tune it to 540kHz while holding it near your transmitting antenna. You should clearly hear the modulating tone in your AM radio. Change the tone to different frequencies and listen again. You are now broadcasting AM radio. Move your radio about the lab and see how far away from your antenna you can pick up the signal. You will achieve maximum range with the carrier amplitude set at maximum output and with the 10 Ω resistor shorted out. Rotating the loop antenna will affect its output. **The output is greater perpendicular to the edge of the loop, and lower perpendicular to the plane of the loop.**

When you are through listening to your test tones over 540kHz, tune your function generator back to 455kHz. Retune your antenna by adjusting the value of the trimmer and/or the fixed capacitors so that the current in the antenna is once again a maximum. Now disconnect your antenna while you build the circuit for experiment 5.

***Questions:***

Q4.2 With the 10 Ω resistor shorted out, what is the resistance in the series resonant circuit?

Q4.3 Can this resistance be adjusted or reduced to zero?

Q4.4 Calculate the bandwidth of this series resonant circuit.

Q4.5 What would be the effect on the transmitted signal if the bandwidth of the transmitter were too small [Q too high]?

Q4.6 What would happen if we reversed the 'scope leads that are connected across the 10 Ω resistor?

Q4.7 Calculate the length of one wavelength at 540kHz.

***Experiment 5: Receiving the signal from your transmitting antenna.***

In this last experiment, we will make some changes to the transistor circuit you built-in experiment 2. We will add another parallel tuned circuit as part of a receiving antenna so that you can pick up

what you transmit much the same way an AM radio does. You will be using what is known as a *loopstick* receiving antenna: a ferrite rod with an antenna coil/transformer wound around it. In parallel with the large primary winding [receiving antenna] you will again place a capacitor to resonate with the inductor and therefore provide sensitivity to only one frequency at a time. If this were a "real" radio, instead of using a combination of fixed capacitor and trimmer for this purpose, you would be using a varactor diode or a variable capacitor that would have a huge adjustable range so that you could tune the whole AM band.

The inductor you will be using has a primary inductance of about 723μH and a turns ratio of 40:1 primary to secondary. This turns ratio allows the high impedance primary circuit to be coupled to the low-impedance input of the transistor stage. The step-down transformer reduces the source impedance of the coil to nearly zero to avoid losses when driving a low- impedance transistor input. [Another way of looking at this is that the transformer steps up the low value of input impedance of the transistor amplifier so that when it is reflected over to the primary it is large enough to prevent it from lowering the bandwidth of the resonant primary circuit.]

This receiving antenna has nulls off the ends of the rod, and is most sensitive in the direction perpendicular to the rod's long dimension.

Calculate the value of capacitance you will need to resonate the primary at 455kHz. Once again, make up this value from a parallel combination of fixed capacitors and a trimmer capacitor. Build the receiving antenna into your transistor amplifier as shown in figure 8. ***Be very careful with the fine wires of the antenna coil.*** You will again need to solder some solid hookup wire to these leads in order to insert them into the protoboard. Obtain a piece of double-sticky foam tape about ½" square from the stockroom window and stick it down to your protoboard next to the point where the antenna coil connects into the circuit. Slide the ferrite rod core into the antenna coil and stick one end of the rod onto the double-sticky tape. Note that the transformer coil is loose on the core. Obtain a wooden toothpick and slide it CAREFULLY between the coil and the ferrite core to keep the coil from sliding down the core.

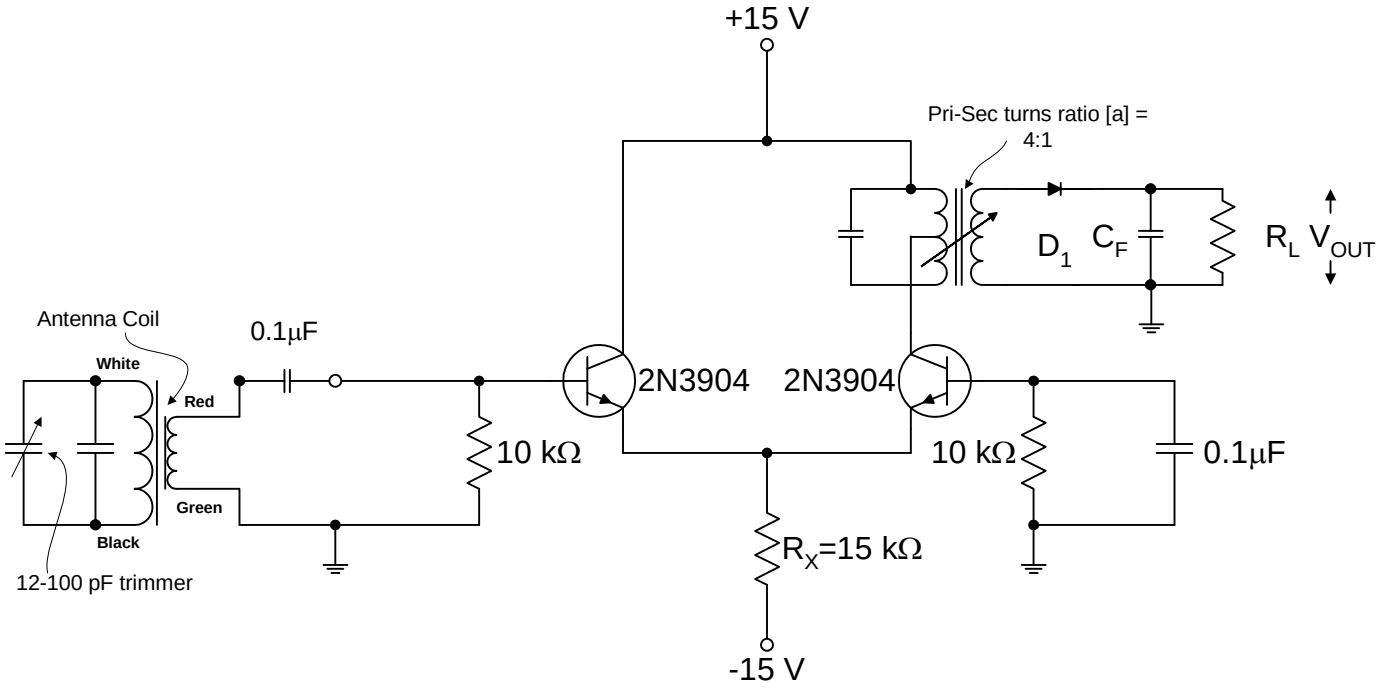


Figure 8: Resonant antenna/antenna coil connected to IF amplifier.

Return to your transmitting antenna and reconnect the function generator. For this experiment we will again use the 455kHz carrier frequency. Connect your 'scope across the secondary of the IF transformer just before the detector diode to monitor the carrier signal strength. Adjust the function generator output and watch your 'scope for indication of a carrier. [Your transmitting antenna should be about 3 feet away from your receiving antenna at this point.] With enough drive into your transmitting antenna to provide a visible signal on the 'scope, adjust your trimmer capacitor for a peak. If a clear peak in the carrier at the IF transformer primary is not obtainable, adjust the value of any fixed capacitors you are using to resonate the antenna coil primary. [***Once again, you may find it easier to compare the phase of the function generator output with the phase of the transformer secondary signal in order to locate the maximum.***] Once the capacitor is correctly adjusted, remove the toothpick between the coil and the ferrite core and GENTLY slide the coil along the core until you see maximum output on the 'scope. You should readjust the trimmer cap now, as moving the coil will change the inductance slightly. Interactive adjustments are a fact of life in RF design!

If you don't have a decent signal level at the primary of your IF transformer, you can obtain more gain in the IF amplifier by adjusting the value of $R_X$. The gain of circuits of this type is primarily dependent on the value of the transistor collector current. If you replace $R_X$ with a 10kΩ potentiometer from your kit in series with a 5.1kΩ fixed resistor, you will be able to adjust the circuit gain by adjusting the pot. This works because $R_X$ is the sole current-setting resistor for both transistors, which split the current through $R_X$ equally.

Once you have a large enough signal at the primary of the IF transformer, move the 'scope leads across $R_L$ [$V_{OUT}$]. With the modulation turned off at the function generator, the only signal you should see across $R_L$ will be the DC voltage due to the rectification of the carrier. This value will vary depending on your signal strength. If you now program your function generator to produce a 400 Hz modulating frequency at 80% modulation, you should see the 400Hz audio signal riding on top of the DC voltage at your detector output.

While keeping the carrier frequency output level constant, and also the distance between the transmitting and receiving antennae constant, [in other words don't move anything!] program in the following audio frequencies: 400 Hz, 1000 Hz, 3000 Hz, 5,000 Hz, all at 50% modulation. Record the output levels as observed on your oscilloscope. If the output at 5000 Hz relative to the 400 Hz output is no longer down by 3dB, you will have to adjust either the value of your capacitor $C_F$ to correct this or, if the bandwidth is not correct [remember that $R_L$ determines the bandwidth of the circuit], you will need to change $R_L$ and take all the measurements above again. ***Be sure not to move your antenna or your receiver while you are making these measurements!***

***Questions:***

Q5.1 In a previous experiment you carefully adjusted the value of the detector equivalent resistance to tailor the bandwidth of the IF transformer so that it would just accept 455kHz +/– 5000 Hz. Now you have added a second tuned circuit to your receiver. If this new tuned circuit were to have exactly the same "Q" and bandwidth as the first tuned circuit, what would happen to the overall bandwidth of the receiver?

Q5.2 What can you say about the steepness of the bandwidth response curve with two tuned circuits? [A bandwidth response curve is just the inverse of the curve in figure 4, except that the Y-axis represents the output voltage.]

Q5.3 For the measurements you made of the audio output in the paragraph above, record the output voltage vs. audio output frequency in a table so that you can compare these values with the values from the single tuned circuit of Experiment 3.

Q5.4 Record the value of $R_X$ that you ended up using.

Q5.5 By now you should have noticed that the output signal level will vary greatly depending on the distance of the receiving antenna from that of the transmitting antenna, and also with the power input to the transmitting antenna. You have also noticed that there is a DC voltage produced across the detector load resistance that is proportional to the received carrier signal strength. Given that you have also observed that the gain of the IF amplifier can be adjusted by varying $R_X$ in order to vary the transistor collector currents, can you think of a way that the carrier-proportional DC voltage can be used to automatically adjust the gain of the IF amplifier?